ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM033

OBSERVATION OF COHERENT TERAHERTZ BURSTS DURING LOW-ENERGY OPERATION OF DELTA*

C. Mai†, B. Büsing, S. Khan, A. Radha Krishnan, W. Salah[1], Z. Usfoor,V. Vijayan,
Center for Synchrotron Radiation (DELTA), TU Dortmund University, Germany
[1]on leave from Department of Physics, The Hashemite University, Zarqa, Jordan

Abstract

The electron storage ring DELTA, which is operated by TU Dortmund University, can be operated at a reduced beam energy down to 450 MeV instead of 1.5 GeV. If a single bunch at low energy is stored, the bunch charge threshold for the emission of THz bursts can be exceeded. Using a fast Schottky-barrier detector, coherent synchrotron radiation bursts of THz radiation were detected. Turn-by-turn data of the THz bursting behavior as function of the bunch charge and bursting spectrographs are presented.

INTRODUCTION

Coherently emitted THz radiation is routinely generated at the short-pulse facility of the 1.5-GeV electron storage ring DELTA which is operated by the TU Dortmund University. Here, THz diagnostics is used to optimize the interaction of ultrashort laser pulses and a single electron bunch to generate VUV radiation by applying the coherent harmonic generation (CHG) [1] scheme and, more recently, the echo-enabled harmonic generation (EEHG) [2, 3] scheme.

At many light sources (e.g., the Metrology Light Source in Berlin [4]), the emission of coherent synchrotron radiation in the THz range due to the microbunching instability [5] was observed with intense, short bunches. In standard operation of DELTA (see parameters in Tab. 1), these so-called THz bursts are not visible. Recently, signals from THz bursts were acquired in a low-energy operation of the storage ring.

Table 1: Parameters of the Electron Storage Ring DELTA

standard beam energy	1.5 GeV
circumference	115.2 m
revolution time	384 ns
multibunch current	130 mA (max.)
single-bunch current	20 mA (max.)
bunch duration	80 ps (FWHM)
horizontal beam emittance	18 nmrad
relative energy spread	7×10^{-4}
momentum compaction factor	5×10^{-3}

LOW-ENERGY OPERATION OF THE DELTA STORAGE RING

The beam energy of the DELTA electron storage ring is 1.5 GeV during user operation. However, the ring was designed to be run at energies as low as 450 MeV for the operation of a storage-ring free-electron laser in the past [6].

* Work supported by the BMBF under contract 05K22PE4.
† carsten.mai@tu-dortmund.de

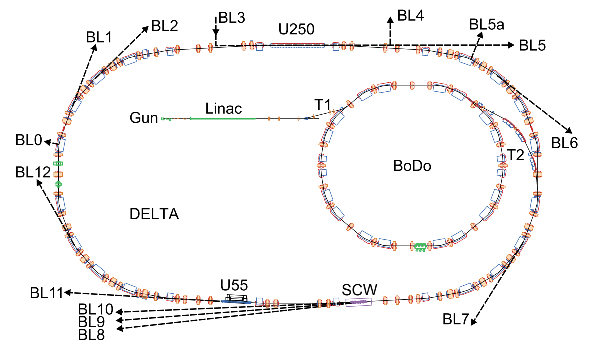

Figure 1: Layout of DELTA comprising the linear accelerator (Linac), the booster synchrotron (BoDo) and the electron storage ring.

Figure 1 shows a layout of the accelerator complex. Since an efficient injection at low energies requires sophisticated tuning of the magnetic fields and timings of the booster synchrotron, it was recently tested to perform a single-bunch injection at 1.5 GeV and ramp down the storage ring afterwards. By using look-up tables for the magnet currents and stepwise ramping, a low-energy operation downto 800 MeV was achieved. The procedure allows to work with a high bunch current of about 10 mA in a broad range of beam energies. The beam lifetime reduces to about 30 min at a beam energy of 800 MeV because of the energy dependence of the Touschek effect.

THZ BURSTING

Synchrotron radiation at wavelengths longer than the charge distribution which causes the radiation phenomenon, is emitted coherently. The spectral power of the coherent radiation is proportional to the number of electrons squared. Another mechanism leading to the emission of THz radiation is the coherent synchrotron radiation (CSR) impedance. Above a certain bunch current threshold, the CSR impedance leads to a modulation of the longitudinal phase space, which gives rise to the formation of substructures in the longitudinal electron density leading to the emission of CSR.

In the parallel-plates model [7], the influence of a conductive vacuum chamber of height $2h$ on an electron bunch is modeled. The threshold bunch current I_b of this instability is [8, 9]

$$I_\mathrm{b}^\mathrm{th} = \gamma I_A \sigma_\delta^2 \alpha_c R^{-1/3} \sigma_{z,0}^{1/3} \left(0.5 + 0.12 R^{1/2} \sigma_{z,0} h^{-3/2}\right) \quad (1)$$

with the Lorentz factor γ, the Alfvén current I_A, the relative energy spread σ_δ, the momentum compaction factor α_c,

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM033

the bending radiaus R and the natural bunch length $\sigma_{z,0}$. The dependence on the Lorentz factor reduces the threshold for lower beam energies. Measurements of coherent THz radiation were performed at beam energies between 1.0 GeV and 1.2 GeV.

MEASUREMENT SETUP

The coherent radiation emitted from a 20-degree bending magnet was focused to a fast, broadband, quasioptical Schottky diode (ACST GmbH, Hanau, Germany) which is sensitive in the spectral range from several 10 GHz to 2 THz. The data was stored in sets of 100 million data points acquired at a sampling rate of 1 GS/s using a fast oscilloscope (Teledyne LeCroy WavePro 804HD).

Starting with a single-bunch current of about 10 mA, the beam energy was ramped down until the first coherent emission became visible. Due to the limited lifetime, the beam current decreased significantly within minutes and the coherent emission stopped. To study the bursting threshold, the beam energy was lowered further until coherent emission set in again.

BURSTING REGIMES

Figure 2 shows the evolution of coherent THz radiation over 5000 consecutive revolutions at a beam energy of 1050 MeV and a bunch current of 6.1 mA. In this configuration, a minimum signal is always present while a strong burst rises and decays over approximately 2000 revolutions. On top of that, sharp spikes with a period of about 100 revolutions are visible.

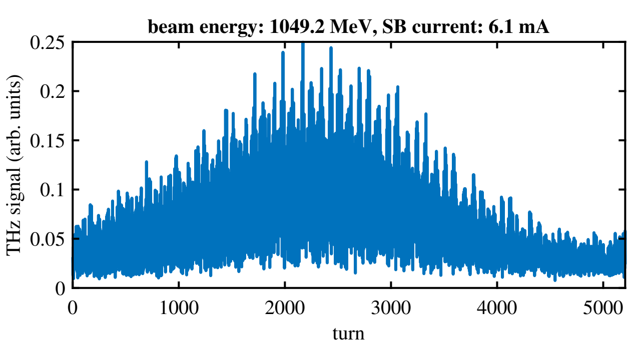

Figure 2: Coherent THz pulses observed over many turns in a high-current regime (6.1 mA).

A slightly lower beam current leads to a loss of the coherent signal. However, the signal can be observed again at a beam energy of 1040 MeV and a beam current of 5.4 mA. A measurement in this regime is shown in Fig. 3. Here, two bursts, rising and decaying over about 600 revolutions each, are observed. The two measurements in Fig. 2 and Fig. 3 show a significantly different temporal evolution of the THz signal.

STUDY OF THE BURSTING THRESHOLD

For a more systematic analysis of the bursting threshold and different bursting regimes, frequency-domain data were

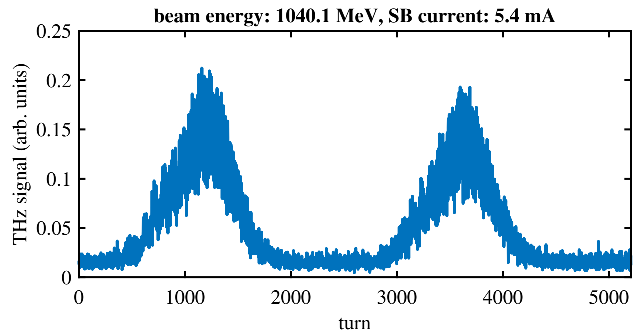

Figure 3: Pulse trains of coherently emitted THz radiation at lower beam current.

analyzed. Figure 4 shows fast Fourier transforms of the time-domain THz data as function of the beam current. At a beam energy of 1 GeV, above a bunch current of 4.7 mA, the spectrograms are broadband. Below this threshold, coherent emission is still visible above 4.2 mA at harmonics of 22.8 kHz which is the synchtron oscillation frequency. Below this current, no coherent emission is visible.

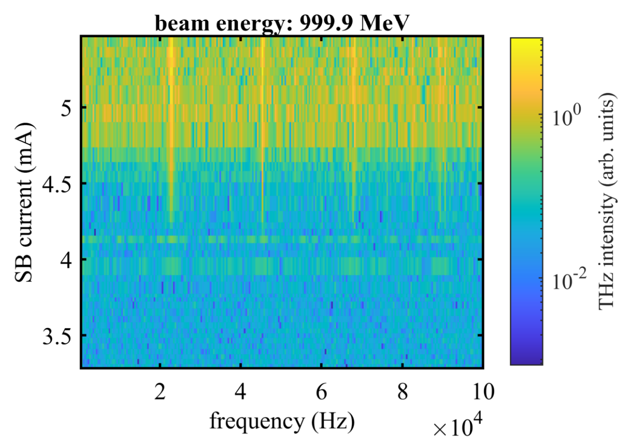

Figure 4: Spectrograms of THz signals as function of the single-bunch current (see text for details).

The bursting intensity as function of the beam current is shown in Fig. 5 for an arbitrarily chosen frequency of f = 10 kHz (blue) and the synchrotron oscillation frequency of f_s = 22.8 kHz. The coherent signal observed at the synchrotron tune is stronger and sets in at a lower bunch current.

During first measurements, the bursting threshold could be studied at four different beam energies between 1.0 GeV and 1.2 GeV. Figure 6 shows the corresponding data (red) and the correlation between beam energy and threshold current (blue line). The curve follows the linear dependence on γ as suggested by Eq. 1. The extrapolation to the standard beam energy of 1.5 GeV proves that the occurence of THz bursting is unlikely to be seen in standard operation due to the high threshold current of approximately 17 mA which is also close to the achievable bunch current limit and far above the typical bunch current in user operation.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM033

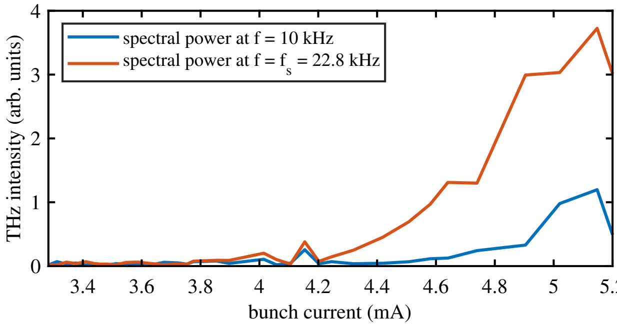

Figure 5: Comparison of the spectral power of the coherent emission as function of the beam current observed at the synchrotron tune (red) and aside from the synchrotron tune (blue).

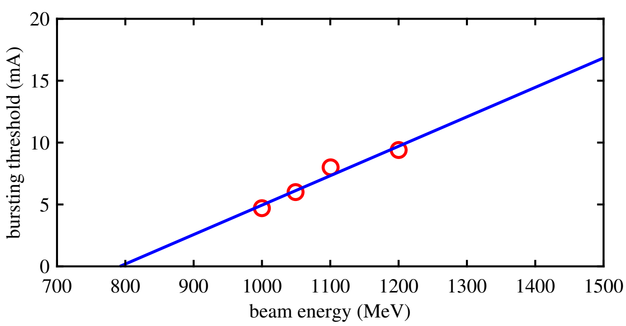

Figure 6: Measurement (red) of the bursting threshold as function of the beam energy and extrapolation to the nominal beam energy of 1.5 GeV.

CONCLUSIONS & OUTLOOK

While it is not possible to observe an effect of the microbunching instability in standard operation of DELTA, which is a multi-bunch filling of 144 bunches with an average bunch current of 0.9 mA, it was shown that the THz bursts occur at lower energy. Studies of the threshold indicate that a bunch current of about 17 mA would be necessary to achieve bursting at the standard beam energy of 1.5 GeV. Compared to the emission of THz radiation at the short-pulse facility, which uses the interaction of ultrashort laser pulses with 1 kHz repetition rate and a single bunch, the bursting occurs at a higher repetition rate of 2.6 MHz at a comparable peak intensity of the THz pulses, meaning that the average power is larger by three orders of magnitude.

Further studies will include spectral measurements to characterize the THz pulses. A setup for electro-optical diagnostics of THz pulses is currently built and will help to understand the spectro-temporal properties of the THz bursts.

Experiments at Synchrotron SOLEIL showed [10] that the THz bursting can be stabilized by implementing a feedback acting on the RF voltage. At DELTA, an RF phase modulation is routinely applied [11]. First experiments indicate that the bursts can be enhanced by correct choice of the phase modulation parameters. A potential stabilization of the bursting by a feedback acting on the phase modulation will be subject to further studies.

ACKNOWLEDGEMENTS

We are pleased to thank our colleagues at DELTA and other institutes, particularly HZB in Berlin, DESY in Hamburg and KIT in Karlsruhe, for their continuous support and advice.

REFERENCES

[1] S. Khan *et al.*, ”Coherent Harmonic Generation at DELTA: A New Facility for Ultrashort Pulses in the VUV and THz Regime”, *Sync. Radiat. News*, vol. 24, pp. 18–23, 2011.

[2] G. V. Stupakov, ”Beam Echo Effect For Generation of Short-Wavelength Radiation”, in *Proc. FEL'09*, Liverpool, UK, Aug. 2009, paper MOOB01, pp. 15–22.

[3] S. Khan *et al.*, ”SPEED: Worldwide first EEHG implementation at a storage ring”, presented at the 14th International Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper MOPM032, this conference.

[4] M. Ries, J. Feikes, P. O. Schmid, G. Wuestefeld, and A. Hoehl, “THz Bursting Thresholds Measured at the Metrology Light Source”, in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPPR046, pp. 3030–3032.

[5] G. Stupakov, S. Heifets, ”Beam instability and microbunching due to coherent synchrotron radiation”, *Phys. Rev. ST Accel. Beams*, vol. 5, p. 054402, 2002.

[6] D. Noelle, ”Delta: Felicita I Lasing in visible range”, *Sync. Radiat. News*, vol. 12, pp. 36–37, 1999.

[7] J. Murphy, S. Krinsky, R. Gluckstern, ”Longitudinal wakefield for an electron moving on a circular orbit”, *Part. Accel.*, vol. 57, pp. 9–64, 1997.

[8] K. L. F. Bane, Y. Cai, G. Stupakov, ”Threshold studies of the microwave instability in electron storage rings”, *Phys. Rev. ST Accel. Beams*, vol. 13, p. 104402, 2010.

[9] M. Brosi *et al.*, ”Fast mapping of terahertz bursting thresholds and characteristics at synchrotron light sources”, *Phys. Rev. AB*, vol. 19, p. 110701, 2016.

[10] C. Evain *et al.*, ”Stable coherent terahertz synchrotron radiation from controlled relativistic electron bunches”, *Nature Physics*, vol. 15, pp. 635–639, 2019.

[11] M. A. Jebramcik, S. Khan, W. Helml, ”Steady-state solutions of split beams in electron storage rings”, *Scientific Reports*, vol. 12, 18383, 2022.